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Potential of Thin Films for use in Charged Particle Tracking Detectors

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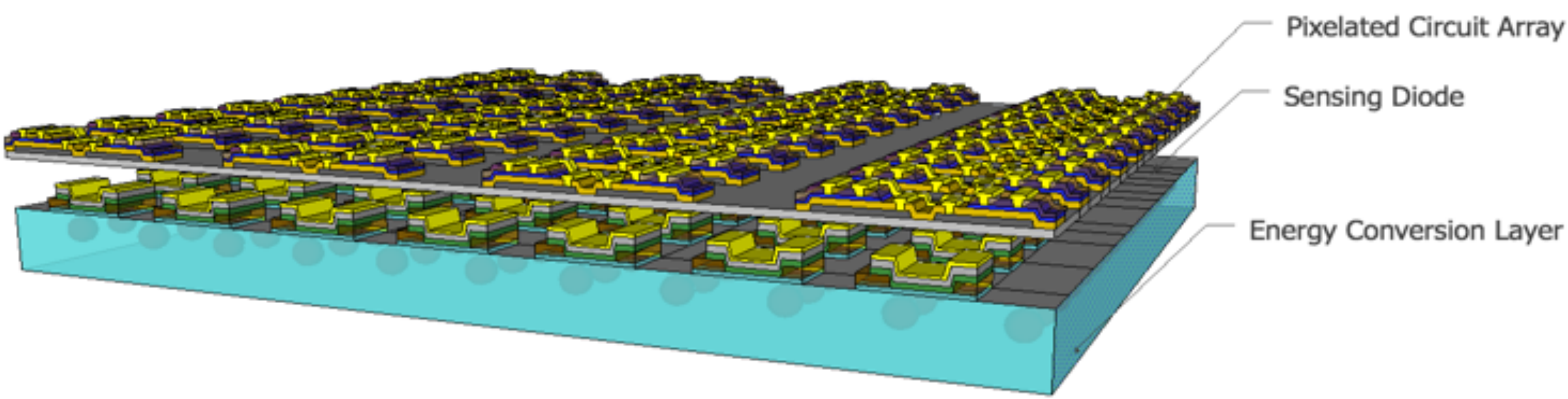
Thin Films

Thin Films: thin layers of materials ranging from nm to μm

- Current popular applications
  - solar cells
  - LCD screens

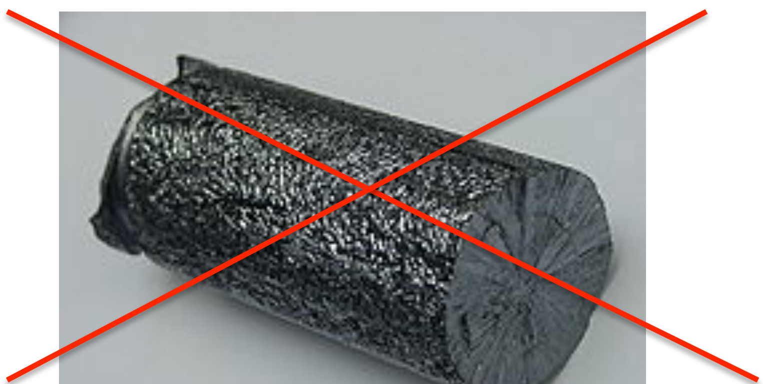
- Thin Films for Particle Detectors:
  - Thin Film Diodes + Thin Film Transistors



TF Fabrication

Thin Film (TF) Fabrication

- Thin Films can be fabricated using
  - chemical bath deposition
  - close-space sublimation
  - Crystals are grown in thin layers on a substrate with high precision
  - Compare to traditional silicon that relies on growing a large crystal and then drilling, etching, etc.
- TF's can be grown at least 200 μm thick
- TF fabrication is much less expensive
  - < \$10 per m^2 for a 2.5 μm thick CdTe film
- TF can be deposited on flexible substrates such as organic polymers and plastics



Polycrystalline silicon rod

TF Design Goals

Design Goals

Meet current tracking performance of a typical tracking detector such as ATLAS

- Charge yield 1,000 – 10,000 electrons
- Energy resolution 5-10%
- Position resolution ~10 µm
- Timing resolution 10-100 ns
- Signal/Noise 2-30

Flexible layers “printed” in large sheets
➔Possibility for unique geometries with less dead space

TF Materials

What materials might work?

Material	Z	Density [g/cm^3]	Radiation length [mm]	Bandgap [eV]	Energy per e–h pair [eV]	Intrinsic resistivity [Ωcm]	Electron mobility [cm^2/(Vs)]	Hole mobility [cm^2/(Vs)]	Electron lifetime [s]	Hole lifetime [s]
Si	14	2.33	93.6	1.12	3.62	320′000	1450	450	10^{-4}	10^{-4}
Ge	32	5.32	23	0.66 at 77 K	2.9 at 77 K	50	36000 at 77 K	42000 at 77 K	10^{-4}	10^{-4}
InP	49/15	4.97		1.35	4.2	$\approx 10^7$	4600	150		
GaAs (bulk)	31/33	5.32	23.5	1.424	4.2	$3.3\ 10^8$	>8000	400	10^{-8}	10^{-9}
CdTe	48/52	6.2	14.7	1.4	4.4	$\approx 10^9$	1000	80	10^{-6}	10^{-6}
$Cd_{0.8}Zn_{0.2}Te$	48/30/52	6		1.6	4.7	$\approx 10^{11}$	1350	120	10^{-6}	$2\ 10^{-7}$
HgI	80/53	6.4	11.8	2.13	4.3	$\approx 10^{13}$	100	4	$7\ 10^{-6}$	$3\ 10^{-6}$
Diamond	6	3.5	122	5.5	13	$>10^{11}$	1800	1200		
a-selenium	34	4.27	29		6–8					

➔ Short list. What else is there?

TF Charge Generation

Estimate Charge Generation in random material:

$$-\frac{dE}{dx} = \frac{Z\rho}{A}\frac{Kz^2}{\beta^2}\ln[\frac{2m_e c^2\beta^2}{I^2(1-\beta^2)} - \beta^2] \propto \frac{Z\rho}{A}$$

For a MIP in a detector with active thickness, x:

$$MIP_{material}(x) = \frac{dE}{dx}\cdot x$$

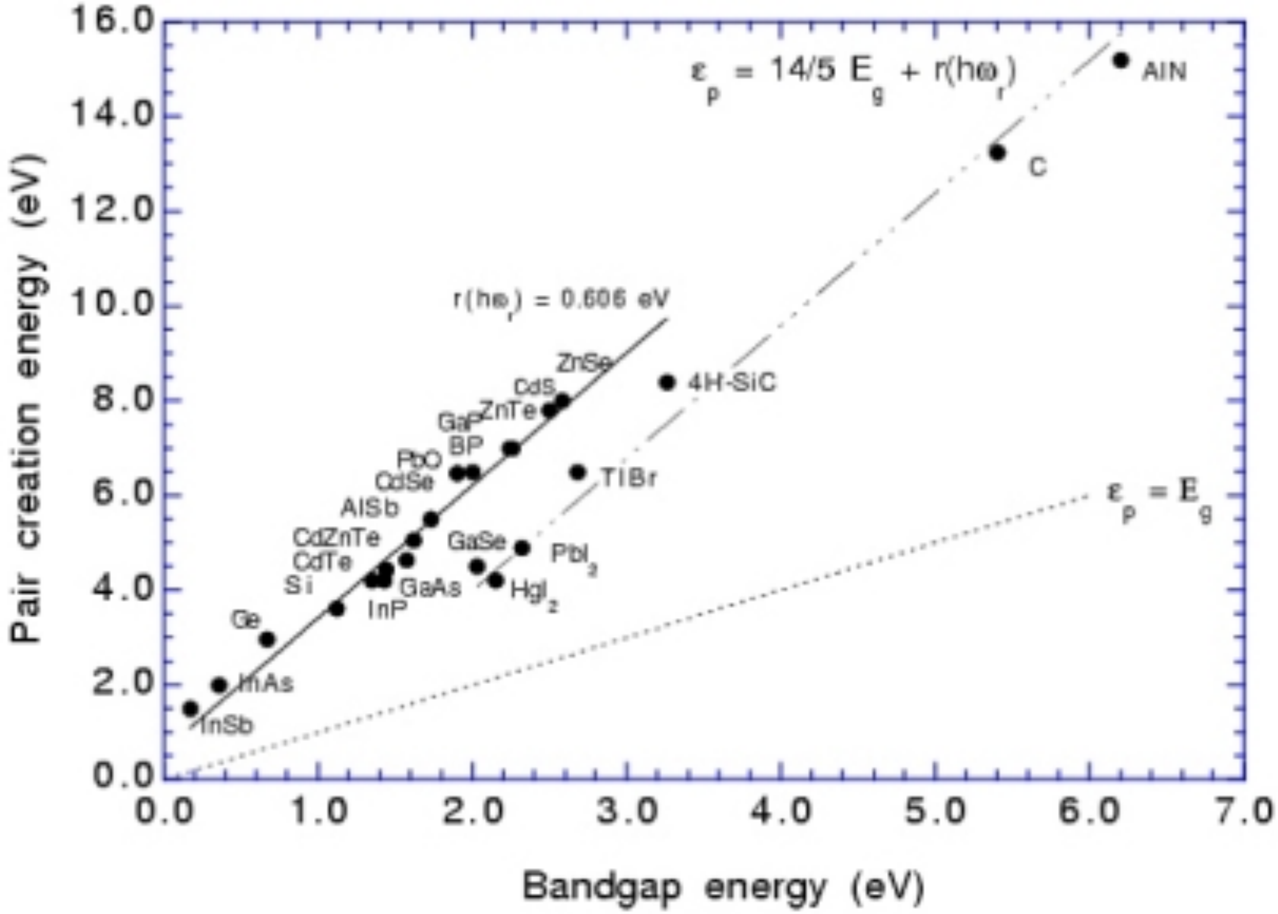
Number of ion pairs produced for incident particle with energy, E_0, and the mean energy to produce an ionization pair, E_i:

$$N_{ion\ pairs} = E_0/E_i$$

TF Charge Generation

Use the bandgap energy, E_g, to estimate E_i: $E_i \propto E_g$

$$E_i \approx 2.0877 \cdot E_g + 1.2122$$



Material	E_g (eV)	E_i (eV)
Ge	0.67	2.96
Si	1.11	3.62
CdTe	1.4	4.43
GaAs	1.43	4.2
diamond	5.5	13

TF Charge Generation

Material	Z	ρ (g/cm^3)	$\frac{-dE}{dx}$ [MeV/(g/cm^2)]	MIP in 10μm (keV)	E_i (eV)	$< N_{e-h\ pairs} >$ in 10 μm
B	5	2.370	1.623	3.85		
Diamond	6	3.51	1.78	6.25	13	0.5k
Si	14	2.329	1.664	3.9	3.62	1.1k
S	16	2.00	1.652	3.30	6.64*	0.5k
Zn	30	7.133	1.411	10.06	8.1*	1.2k
Ga	31	5.904	1.379	8.14		
Ge	32	5.323	1.370	7.29	2.96	2.5k
As	33	5.730	1.370	7.85		
Cd	48	8.650	1.277	11.05		
I	53	4.930	1.263	6.23		
Pb	82	11.350	1.122	12.73		
CdTe	50	6.2	1.26	7.81	4.43	1.8k
CdS	32	4.8	4.0*	19.08	6.49*	2.9k
PbS	49	7.6	6.2*	46.8	1.98*	23.6k
ZnO	19	5.6	4.4*	24.8	8.25*	3.0k
GaAs	32	5.32	1.4	7.45	4.2	1.8k
InP	32	4.97	4.0*	20.5	4.2	4.8k
HgI	66.5	6.4	5.6*	35.8	4.3	8.3k
InSb	50	5.78	4.9*	28.1	1.57*	17.9k
InAs	41	5.67	4.7*	26.8	1.94*	13.8k
HgTe	66	8.1	6.7*	54.7		
CdZnTe	43.3	6	5.0*	29.8	4.7	6.3k
IGZO	29.5	6			7.58*	

*calculated

TF Signal Timing

Signal Timing:
Velocity, v, given mobility, μ, in an electric field E(x), where x is the charge carrier position and W is the depletion width:

$$v(x) = \mu E(x) = \mu E_0 (W - x)$$

$$E_0 = \frac{q_e N_d}{\varepsilon}$$

Then the characteristic time to travel 0.63W:

$$t(x) = \int_{x_0}^{x} \frac{1}{v(x)} dx = \frac{1}{\mu E_0} \int_{x_0}^{x} \frac{1}{(W - x)} dx$$

$$\tau_h = \frac{\varepsilon}{\mu_h q_e N_d} = \rho \varepsilon = \rho \varepsilon_0 \varepsilon_r$$

holes

$$\tau_e \approx \frac{\tau_h}{3}$$

electrons

TF Signal Timing

Material	μ_e $\left(\frac{cm^2}{V\cdot s}\right)$	μ_h $\left(\frac{cm^2}{V\cdot s}\right)$	ε (F/m)	ρ $(\Omega \cdot cm)$	τ_p (ns)	τ_e (ns)
Diamond	1800	1200	5.5	1E+11	1.6 s	4.9 s
Si	1350	480	12	320	34 ns	11 ns
CdTe	1050	100	9.4	1E+9	28 ms	83 ms
CdS	340	50	10			
PbS	600	700	170			
ZnO	130		2			
IGZO	15	0.1				
GaAs	8000	400	12.5	3.3E+8	12 ms	36 ms
InP	4600	150		1E+7		
HgI	100	4		1E+13		
InSb	78000	750				
InAs	33000	460				
HgTe	22000	100	20			
CdZnTe	1350	120		1E+11		

- Need to measure timing directly since we know diamond can have a rise time as fast as ~5 ns

TF Radiation Properties

<u>Radiation Properties</u>

- Want to survive fluences on the order of 10^{13} – 10^{17} for 1 MeV n_{eq}/cm^2

- Expect the electronics to be rad-hard due to the small feature sizes ~20 nm
  - TFT's were exposed to 10 Mrad with a ^{60}Co source with no observed effect

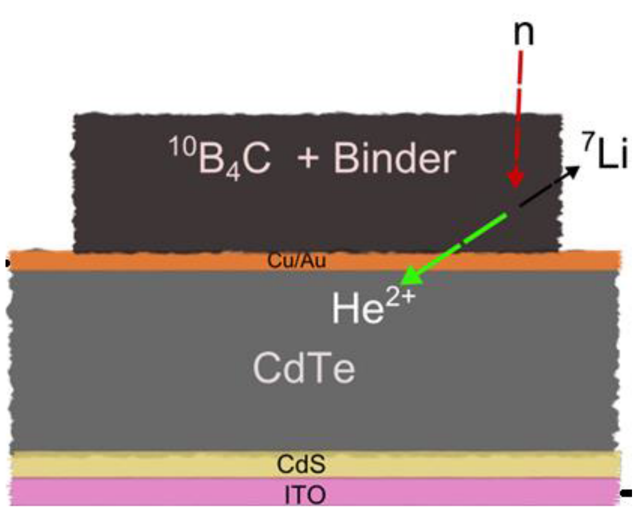
- Displacement damage in the diodes is less well known and needs to be measured
  - Given the less than perfect nature of thin film crystalline structure we can guess that imperfections due to radiation damage will have a smaller effect on performance

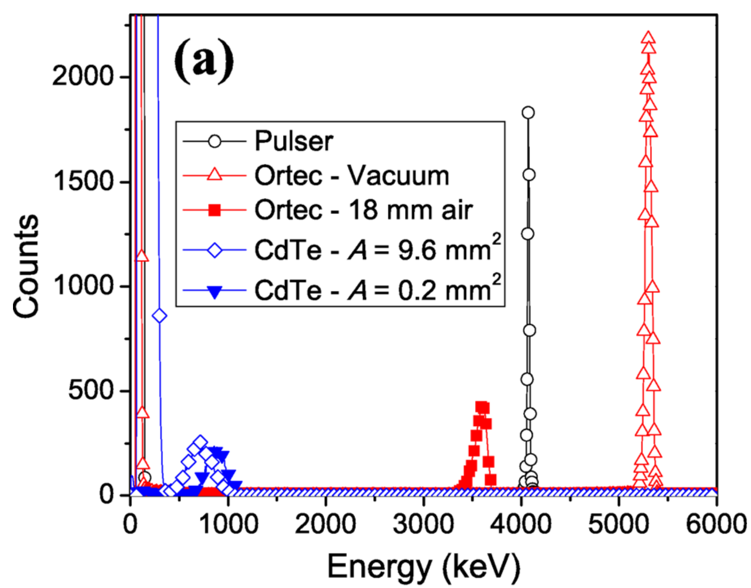
- SEU effects will also need to be studied
  - The low operation voltages will require less charge to be switched
  - Small feature sizes should reduce the probability of charge generation

TF diodes

Started a collaboration with University of Texas Dallas

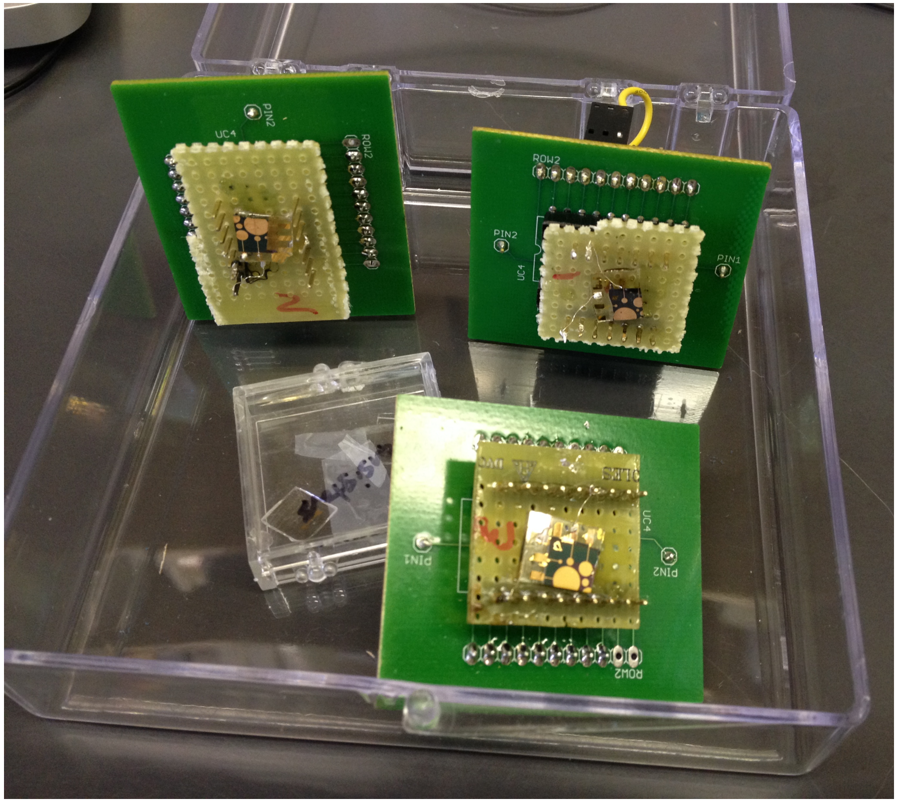
- Already published measurements with TF as neutron detectors
- Use a boron conversion layer for neutrons to interact and emit an α particle
- Used ^{210}Po source with 3500 keV α's
- 6 µm thick CdTe layer with 4 µm thick active area biased at 2 V
- Measure the α particle with > 90% efficiency
- FWHM 27% to 41%

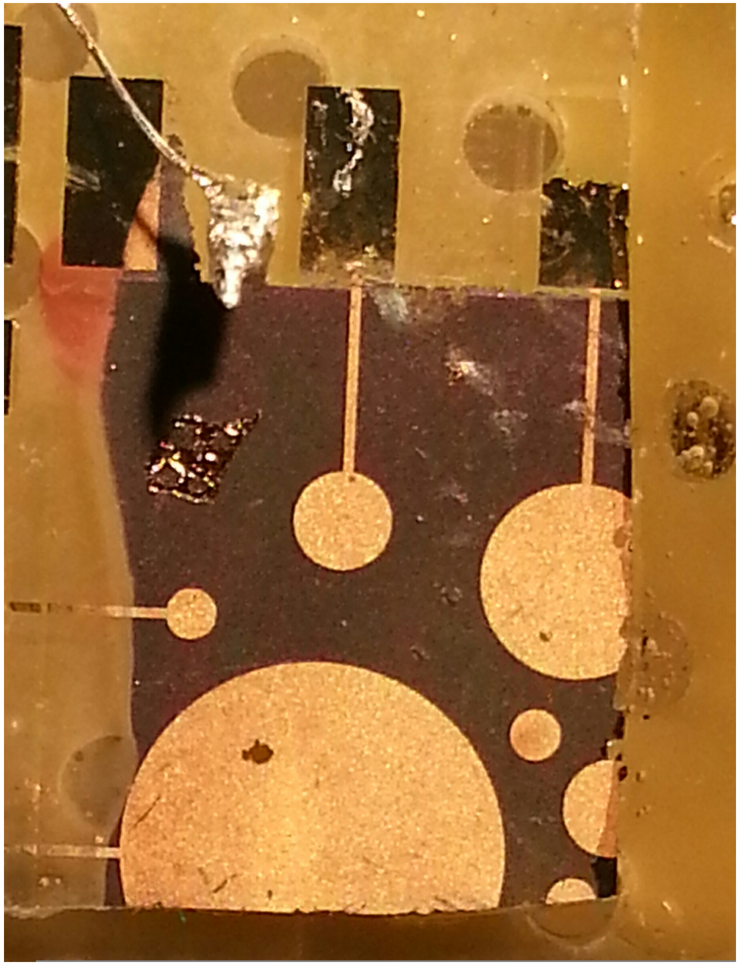




TF Samples

We received the first set of samples from UT Dallas last week:

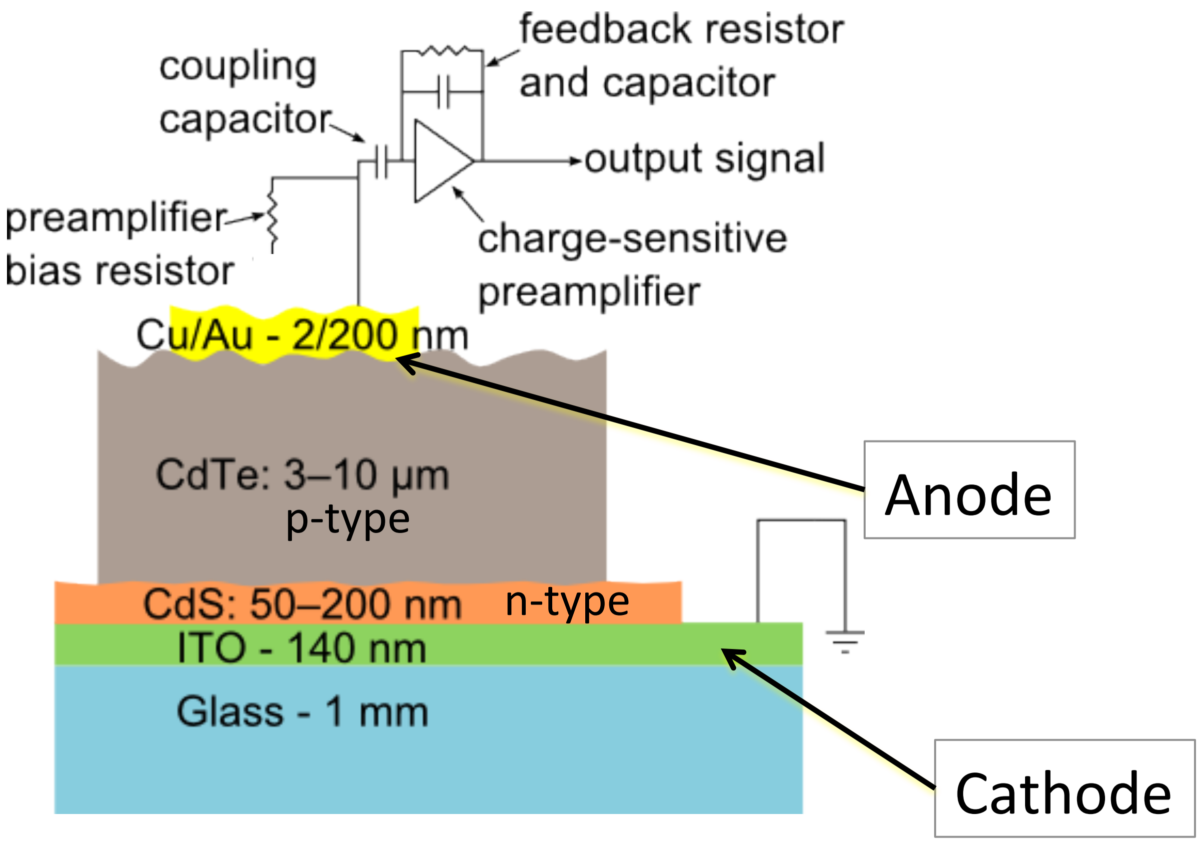




…no measurements at BNL yet

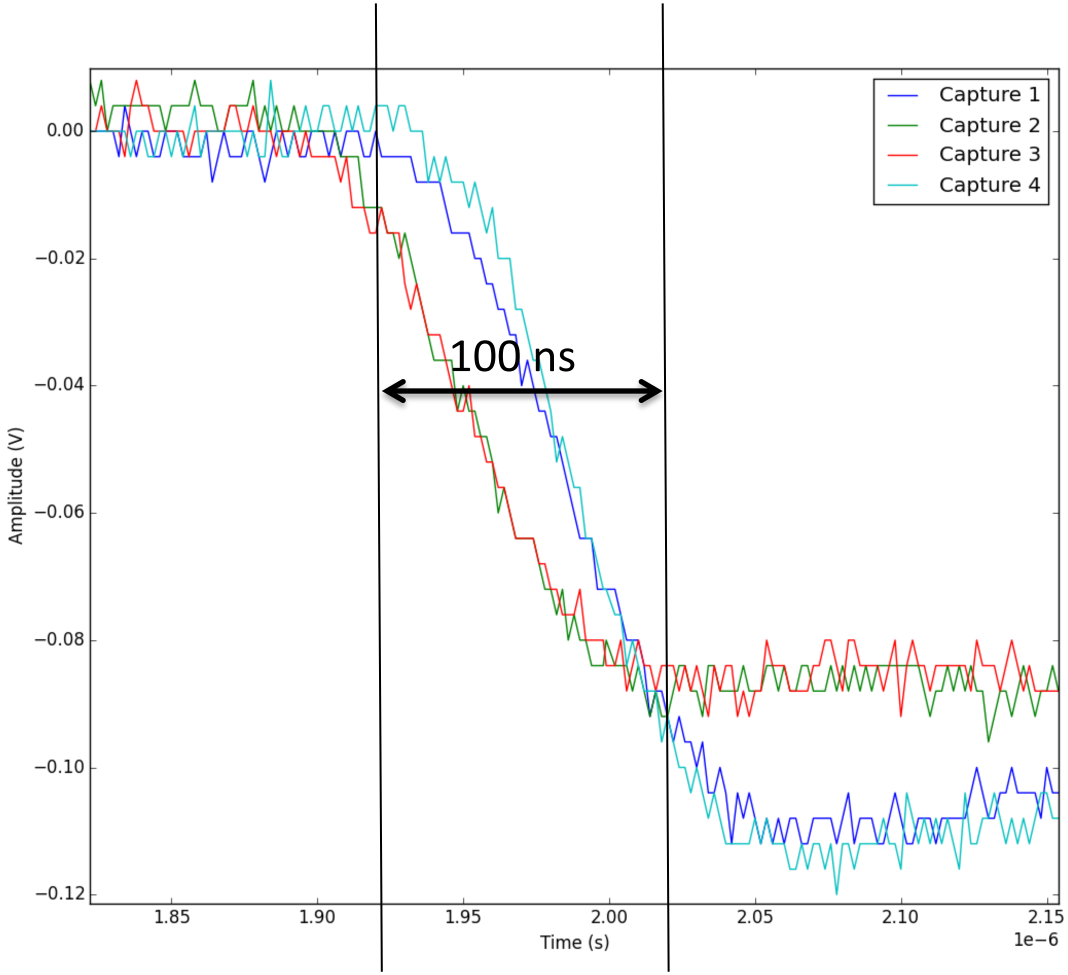
TF

Our samples:
- 5 µm CdTe



TF Signal

Measurement done at UTD:



- ^{210}Po source
- Ortec 109A amplifier
- 1 V reverse bias
- 6 µm thick active area

Plans

Plans for TF samples

Short term:

- Characterization measurements
  - Capacitance
  - Leakage current
  - Diode curve
- Signal measurements with ^{90}Sr source
  - Charge generation
  - Rise-time
  - S/N
  - FWHM
- Radiation damage properties
  - Repeat above after ^{60}Co source irradiation

Medium term:

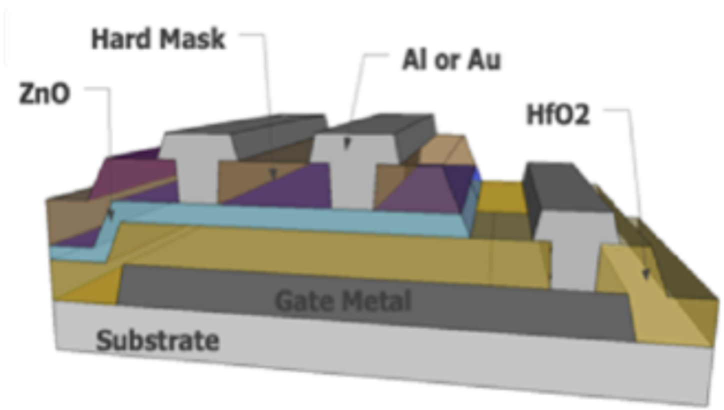
- Different materials
- dE/dx measurements
- Rise-time or characteristic time

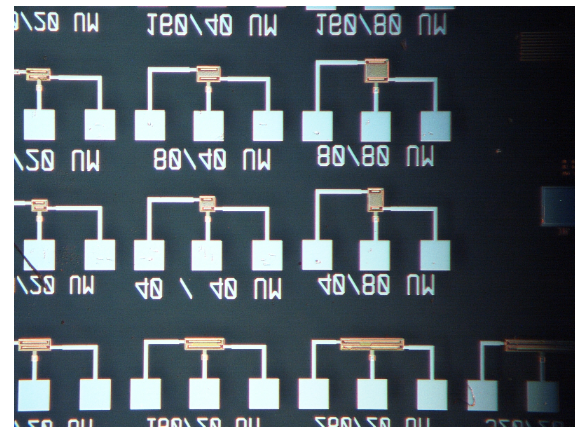
Plans

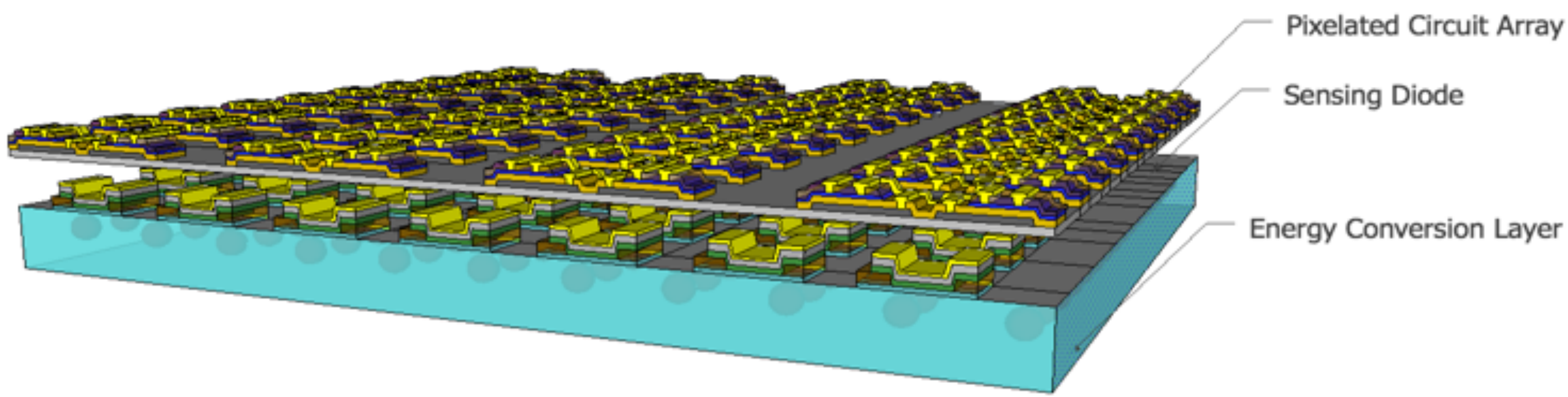
Plans for TF samples

Long term:

- Build a detector with integrated electronics
- Design the circuitry for signal amplification







Summary

Started a collaboration with :

- University of Texas Dallas
  - Israel Mejia
  - John Murphy
  - Lindsey Smith
  - Manuel Quevedo
  - Bruce Ganade
- Benemérita Universidad Autónoma de Puebla
  - Joaquin Alvarado

Paper on the proposed idea:

- Plan to submit to arXiv today

Potential of Thin Films for use in Charged Particle Tracking Detectors

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ABSTRACT: Thin Film technology has widespread applications in everyday electronics, notably Liquid Crystal Display screens, solar cells, and organic light emitting diodes. We explore the potential of this technology as charged particle radiation tracking detectors for use in High Energy Physics experiments such as those at the Large Hadron Collider or the Relativistic Heavy Ion Collider. Through modern fabrication techniques, a host of semiconductor materials are available to construct thin, flexible detectors with integrated electronics with pixel sizes on the order of a few microns. We review the material properties of promising candidates, discuss the potential benefits and challenges associated with this technology, and review previously demonstrated applicability as a neutron detector.